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Manure composition affects net transformation of nitrogen from dairy manures

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Abstract

The plant available nitrogen (PAN) content of dairy manure is commonly calculated using concentration and availability coefficients for organic nitrogen (N) and ammonium N (NH_4), but the carbon (C) fraction of the manure also influences the availability of N over time. We evaluated the interactive effect of manure C and N from nine dairy manures during a 176 days aerobic incubation. All of the manures had appreciable NH_4 content, and varied widely in fibrous C. The incubation was conducted using sandy loam (coarse-loamy, mixed, frigid, Typic Haplorthod) and silt loam (fine, illitic, non-acid, frigid, Aeric Epiaquepts) soils at 25 °C and 60% water-filled pore space. There were clear differences in nitrate (NO_3) accumulation over time, including manures that resulted in net nitrification and net immobilization. For both soils, the rate of nitrification at 7 and 56 days after application, and the amount of NO_3 accumulated at the end of the incubation (176 days) were strongly correlated ($r = -0.88$) with C: NH_4 and also to the ratio of neutral detergent fiber (NDF):NH_4 ($r = -0.90$). The addition of manure C also resulted in significant net immobilization, compared to addition of mineral N fertilizer alone. These studies demonstrate that increased understanding of manure C and N interactions may lead to improved prediction of manure PAN.

Abbreviations: ADF – acid detergent fiber; NDF – neutral detergent fiber; PAN – plant available N; WFPS – water-filled pore space

Introduction

Transformations of N in soil, including indigenous soil N and applied manure N, are strongly controlled by the interaction of environmental and soil factors, and by the composition or quality of the substrate. Significant progress has been made in quantifying the effects of temperature (Griffin and Honeycutt, 2000; Griffin et al., 2002) soil water status (Drury et al., 2003), and soil texture (Griffin et al., 2002; Sørensen and Jensen, 1995; Thomsen et al., 2003) on many aspects of N availability, including the rate and extent of mineralization and nitrification, soil N retention, and potential environmental loss of N. Likewise, opportunities for improving the retention of manure N during storage, handling, and application have been evaluated, with an emphasis on retaining readily available urea or NH_4 in the manure (Atallah et al., 1995; Sørensen and Jensen, 1996). The practical application of these efforts has been to develop coefficients for mineralization of manure organic N (Chadwick et al., 2000; Douglas and Magdoff, 1991; Klausner et al., 1994) or describe the potential recovery of

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the inorganic N fraction of manure (Paul and Beauchamp, 1989; Thomsen, 2001), recognizing that these coefficients are generalized guidelines that commonly do not account for differences in manure composition.

A central feature of many experiments that compare plant available N (PAN) from different dairy manures under standardized conditions is the variability inherent in these nutrient sources. The evaluation of more than 100 dairy manures by Van Kessel and Reeves (2002) is a good example; the concentrations of organic and inorganic N in these manures varied by more than ten-fold (0.4–5.6 kg m^{-3} for organic N and 0.3–4.7 kg m^{-3} for NH_4-N). The proportion of manure organic N mineralized during an aerobic incubation also varied widely, from −29 (net immobilization) to 55%. Numerous research efforts have underscored the importance of manure composition in controlling soil N transformations after application, by either quantifying rapidly available N or slowly mineralizable C. For example, Serna and Pomares (1991) reported strong correlative relationships between rapidly obtainable indices (like $KMnO_4$-extractable N and pepsin-hydrolzable N) and the amount of N mineralizable during aerobic incubation for a range of manures, similar to the earlier results of Castellanos and Pratt (1981). Paul and Beachamp (1989) found that water-soluble C and volatile fatty acid (VFA) concentration of manures and composts were positively correlated with denitrification following incorporation into soil. For manures from ruminant animals, a large component of the variability between manures has been ascribed to differences in ration quality and in bedding materials that result in substantial variation in the degradability of C. Kyvsgaard et al. (2000) evaluated this effect directly, demonstrating that mineralization of sheep manure N after application to soil was related to the C:N ratio of the manure, which was in turn strongly correlated with apparent digestibility of the feed. The results of Sørensen et al. (2003) for transformation of dairy manure N are similar, demonstrating that manure N availability is negatively correlated with ration fiber concentration. After removing NH_4 (by volatilization), Chadwick et al. (2000) reported similar results for slurry and farmyard manures. Van Kessel et al. (2000) followed a similar line of reasoning in evaluating mineralization of feed components, including fibrous C fractions.

The above examples not withstanding, the development of predictive relationships between compositional factors and mineralization (or other transformations) of dairy manure N has not been very successful. This is in contrast to similar evaluations of poultry litter by Gordillo and Cabrera (1997) and Qafoku et al. (2001), who demonstrated that uric acid concentration, alone or in combination with other constituents, was strongly correlated ($r > 0.90$) to rapidly mineralizable N. For dairy manures, Van Kessel and Reeves (2002) found statistically significant correlative relationships between N mineralization and either single constituents (e.g. total N, lignin) or constituent ratios (e.g. C:N_{total}), but the strongest relationship (N mineralization versus acid detergent fiber (ADF):total N) had a correlation coefficient (r) of 0.35. Based on the hypothesis that higher levels of recalcitrant C in manure would lead to either slower N mineralization or, in some cases, net N immobilization, the research reported here uses aerobic incubation methods to evaluate the relationship between manure fibrous C content and the net availability of organic and inorganic dairy manure N fractions.

Materials and methods

Soil and manure resources

Two soils of contrasting texture were used in the incubation experiment described below, as texture has been shown to influence transformation of manure N (Griffin et al., 2002). A sandy loam soil (unnamed series; coarse-loamy, mixed, frigid Typic Haplorthod) was obtained from the 0 to 15 cm layer of a tilled field at the USDA-ARS research site near Newport, ME. The second soil was a Lamoine silt loam (fine, illitic, non-acid, frigid Aeric Epiaquepts) collected in the same way at the Maine Agricultural and Forest Experiment Station, in Stillwater, ME. Initial soil nutrient levels are shown in Table 1, as determined by the modified Morgan extraction (McIntosh, 1969), and inductively coupled plasma emission spectroscopy (ICP), along with particle size distribution estimated using the sieving method of Kettler et al. (2001). Both soils were

Table 1. Characteristics of two soils used in incubation experiments on transformations of dairy manure N

	Sandy loam	Silt loam
Soil pH	5.9	6.3
CEC (meq 100 g^{-1})	4.6	7.0
Total C (g kg^{-1})	25.2	37.1
K (kg ha^{-1} equiv.)	321	107
P (kg ha^{-1} equiv.)	6.8	16.4
Sand (g kg^{-1})	520	110
Silt (g kg^{-1})	400	810
Clay (g kg^{-1})	80	80

sieved (2 mm) while still field-moist, then were air-dried in a thin layer on a greenhouse bench, and stored until needed.

Five dairy manures were obtained from samples previously submitted to the University of Maine Analytical Laboratory, and four additional samples were collected from commercial dairy farms in central Maine. Each manure was homogenized using a large food processor. Organic N concentration in the fresh sample was estimated as the difference between total Kjeldahl N (AOAC Method 978.02; Kane, 1998) and NH_4 concentration determined by distillation of NH_4 with MgO (AOAC Method 973.49). The remainder was frozen (−20 °C), and then freeze dried (−80 °C) and ground (2 mm). Ammonium N concentration of the freeze dried manure was measured following Qafoku et al. (2001), by extracting 0.5 g of manure in 40 mL 1.0 *M* KCl, filtering through a 0.45 μm filter, and determining solution NH_4 concentration colorimetrically on a Lachat[1] Autoanalyzer (Lachat Instruments, Mequon WI). We assumed that organic N concentration was not altered by freeze-drying, so the estimate derived from the fresh sample was used. Neutral detergent fiber (Goering and Van Soest, 1970) concentration of manures was estimated by agitating a 1.0 g sample in an individual pre-weighed Dacron bag, using an automated Ankom 200 Fiber Analyzer (ANKOM Technology, Fairport, NY), rinsing three times, and drying to constant weight. Total C concentration in the manure was determined by thermal conductivity detection following combustion at 1650 °C, on a CE Instruments NA2500 Elemental Analyzer (ThermaQuest Italia S.p.A., Rodano, Italy). All analyses were done in duplicate, and characteristics of the freeze-dried dairy manures are shown in Table 2.

[1]Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Aerobic incubation for net transformation of dairy manure N

Prior to beginning the incubation, soil (150 g dry weight) was weighed into 250 mL square plastic containers. Deionized water was added to bring gravimetric soil water content to 0.20 kg kg^{-1} soil, and the soil was then packed to a density of 1.1 g cm^{-3}. All containers were preincubated at 25 °C for 10 days before amendment with manure.

On Day 0, each manure was added to triplicate samples of each soil, at a rate of 100 mg organic N kg^{-1} dry soil equivalent, along with sufficient deionized water to increase soil water content to 0.25 kg kg^{-1}. The resulting water filled pore space (WFPS) of approximately 60% was maintained through the entire incubation period. As shown by Linn and Doran (1984) and Drury et al. (2003), WFPS in this range is optimal for mineralization and nitrification, with minimal loss of N due to denitrification. The soil + manure was thoroughly mixed for 30 s with a small stainless steel spatula. An unamended control treatment and a fertilizer N treatment (NH_4Cl, applied at 100 mg N kg^{-1} dry soil equivalent) were processed in the same manner. A 3-g sample was taken from each container immediately after mixing. This subsample was placed in a 35 mL centrifuge tube with 25 mL of 2.0 *M* KCl, shaken for 1 h, and centrifuged ($2700 \times g$ for 10 min). The supernatant was decanted, and used to determine initial ($t = 0$) concentration of NO_3 and NH_4. Following Van Kessel et al. (1999) and Van Kessel and Reeves (2002), the difference in soil NH_4 concentration between manure amended and unamended samples was used to estimate NH_4 input from the manure (Calc. NH_4; Table 2), and was used in subsequent calculations of net N transformations. Immediately after sampling, the soil was repacked to the initial density, and the container was capped. Soil NO_3 and NH_4 concentrations were determined for each vessel 1, 3, 7, 14, 28, 56, 108, and 176 days after initiation. At each sampling time,

Table 2. Characteristics of freeze-dried dairy manures used in incubation experiments on transformation of dairy manure N

Manure	$g\ kg^{-1}$ Dry matter							
	Original dry matter	Organic N	Extr. NH_4[a]	Calc. NH_4[b]	Total N[c]	Organic matter[d]	Total C	NDF
A	171	17.1	10.0	7.7	27.1	742	393	411
B	35	40	22.8	15.8	62.8	719	415	162
C	72	20.8	13.4	7.5	34.2	864	458	504
D	42	26.2	13.7	7.7	39.9	767	418	391
E	81	16	5.9	4.4	21.9	855	449	622
F	85	21.2	2.7	3.0	23.9	724	385	420
G	117	17.9	9.3	6.1	27.2	811	430	561
H	141	12.1	1.8	2.6	13.9	869	451	617
I	106	18.9	5.6	5.0	24.5	849	443	560

[a]Determined by direct extraction of manure in 1.0 *M* KCl.
[b]Estimated as difference in extractable NH_4 from amended and unamended soil at time (t) = 0.
[c]Estimated as organic N + KCl-extractable NH_4.
[d]Mass lost during ignition of sample for 2 h at 450 °C/initial sample mass.

soil was quickly stirred, sampled, and repacked. Extraction and N determinations were as on Day 0. All containers were aerated for 1 h day^{-1} for the first 2 week, and 1 h every 2–4 days thereafter. Soil water content was adjusted periodically throughout the incubation period to maintain 60% WFPS, accounting for changes in soil mass and volume.

Cumulative net nitrification (N_{cum}), soil concentration of manure-derived NH_4 (N_{amm}), and manure organic N mineralized (N_{org}) at each sampling time (t) was defined similar to Griffin and Honeycutt (2000):

$$N_{cum}(\text{mg kg}^{-1}\text{soil}) = \{[NO_3]_t - [NO_3]_{t=0}\}_{\text{amended}} - \{[NO_3]_t - [NO_3]_{t=0}\}_{\text{unamended}} \quad (1)$$

accounting for changes in soil NO_3 concentration between $t = 0$ and t, and correcting for the N nitrified in the unamended soil. Similarly,

$$N_{amm}(\text{mg kg}^{-1}\text{soil}) = \{[NH_4]_t - [NH_4]_{t=0}\}_{\text{manure}} - \{[NH_4]_t - [NH_4]_{t=0}\}_{\text{unamended}} \quad (2)$$

$$N_{org}(\text{mg kg}^{-1}\text{soil}) = \{[N_i]_t - [N_i]_{t=0}\}_{\text{manure}} - \{[N_i]_t - [N_i]_{t=0}\}_{\text{unamended,}} \quad (3)$$

where N_i is the sum of NO_3 and NH_4 at time, t.

Both zero-order (linear) and single exponential (non-linear) equations were evaluated to model cumulative net nitrification and net mineralization over time. These linear and non-linear equations took the following forms, respectively:

$$N_{cum} \text{ or } N_{org} = a + b^{*}\text{day} \quad (4)$$

$$N_{cum} \text{ or } N_{org} = N_0[1 - \exp^{(-k^{*}\text{day})}], \quad (5)$$

where a is Y-axis intercept, b is slope, N_0 defines the size of the N pool that can be nitrified or mineralized, and k is the rate constant. Equations were fit using all data points, and parameters were estimated using either linear regression (Eq. 4) or non-linear curve fitting via Marquardt iteration (Eq. 5) (SYSTAT, Version 10.0; SPSS Corp., Chicago IL). Net transformation rate at any point in time, t, is the slope (b) in Eq. 4 and the first derivative of the resulting regression line for Eq. 5. The estimate of net mineralization for each manure is the slope of the linear regression (change in inorganic N vs. time). In estimating the slope (b), we also obtain 95% confidence interval around the estimated parameter. As in our previous publications (Griffin and Honeycutt, 2000; Griffin et al., 2002), treatments are deemed significantly different when confidence intervals did not overlap.

Results and discussion

NH_4 concentration in freeze-dried dairy manures

Several research reports have indicated that freeze-dried manures are not suitable for evaluating nitrification of manure NH_4, because of partial or complete loss of NH_4 during the freeze-drying process, similar to volatile loss during oven-drying (Van Kessel et al., 1999). Others (Gordillo and Cabrera, 1997; Mahimairaja et al., 1990) have found that NH_3 losses from freeze-drying are minimal. As indicated in Table 2, the manures used here had a range of NH_4 concentration after freeze-drying, ranging from 1.8 to 22.8 g kg^{-1} DM, based on direct extraction using 1.0 *M* KCl. It is likely that some NH_4 was lost during the freeze-drying process. For comparison, Klausner (1989) reported ranges of 3–21 and from 11 to 44 g NH_4 kg^{-1} DM, for solid and liquid dairy manures, respectively. Similarly, Van Kessel and Reeves (2002) reported an approximate range of 3–44 g NH_4 kg^{-1} DM , including both solid and liquid dairy manures. The subsequent calculations were made using NH_4 extracted at $t = 0$ to standardize incubation data, as done by Van Kessel et al. (1999) and Van Kessel and Reeves (2002). In comparing NH_4 extracted directly from the manures and $t = 0$ extraction of manure amended soil, the slope of the regression between these two variables is 0.59 (Figure 1), indicating that direct extraction is more efficient at removing N from the freeze-dried manures. Although this may be interpreted as meaning that up to 40% of applied NH_4 is either abiotically fixed or immobilized by microbes, the time frame between stirring the soil + manure mixture and extraction with 2 *M* KCl is very short (< 5 min), and the recovery of NH_4 from inorganic N fertilizer was 99.6%.

Net transformations of dairy manure N

Nearly all of the freeze-dried manures and the inorganic N fertilizer resulted in net nitrification (i.e. accumulation of NO_3 in excess of unamended control) in both the sandy loam and silt loam soils. However, as shown in Table 3, the regression form and parameter estimates varied considerably among manures. Five of the nine manures, and the inorganic fertilizer N, resulted in a pattern of net nitrification over time that was best modeled using an exponential, single pool model as in Eq. 5, where NO_3 accumulates rapidly early in the incubation (3–5 week), then more slowly. This pattern of net nitrification is common for manures that contain significant NH_4 at the time of application, and is similar to observations with fresh (not freeze-dried) manures (Griffin et al., 2002; Sørensen and Jensen, 1995). For all of these manures (A, B, C, D, and G) and the inorganic fertilizer N treatment, this pattern of nitrification was the same for both soils, and in no instance was a significant difference in the rate constant, *k*, noted between the two soils. Only a single manure (C) resulted in a different estimate for the size of the N pool that potentially could be nitrified (i.e. N_0 in Eq. 5).

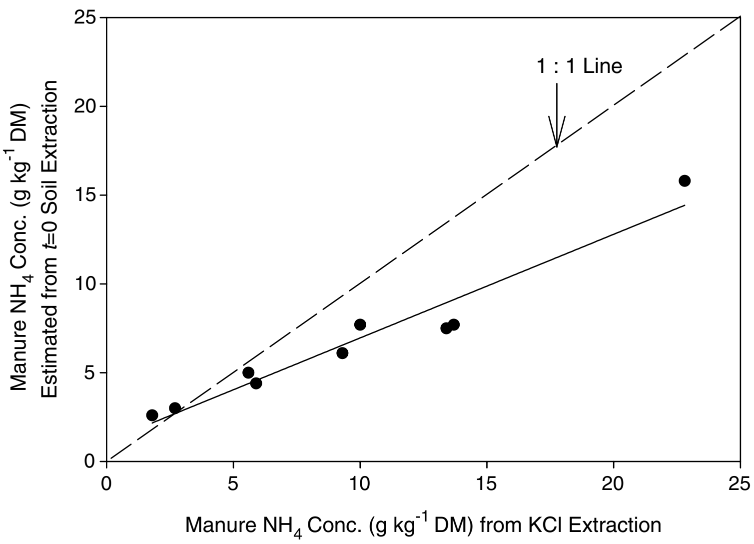

Figure 1. Relationship between manure NH_4 concentration determined by direct extraction in 1.0 *M* KCl and estimated by difference in extractable NH_4 in amended and unamended soils at time (t) = 0.

Table 3. Net nitrification (N_{cum}) of fertilizer and dairy manure N exhibiting exponential ($N_{cum} = N_0\ (1-e^{(-k*DAI)})$ and linear ($N_{cum} = a + b$*DAI) trends for 176 days after incorporation (DAI) into soil

N source	Sandy loam soil	R^2	Silt loam soil	R^2	Diff. between soils
Exponential model for nitrification					
Fertilizer N	$97.75\ (1 - e^{(-0.0286*DAI)})$	0.93	$102.89\ (1 - e^{(-0.0457*DAI)})$	0.94	NS
Manure A	$33.76\ (1 - e^{(-0.0538*DAI)})$	0.77	$28.27\ (1 - e^{(-0.0220*DAI)})$	0.89	NS
Manure B	$45.73\ (1 - e^{(-0.0306*DAI)})$	0.87	$47.11\ (1 - e^{(-0.0543*DAI)})$	0.94	NS
Manure C	$29.57\ (1 - e^{(-0.0204*DAI)})$	0.83	$18.88\ (1 - e^{(-0.0603*DAI)})$	0.77	* (for N_0)
Manure D	$27.25\ (1 - e^{(-0.0484*DAI)})$	0.75	$33.34\ (1 - e^{(-0.0499*DAI)})$	0.87	NS
Manure G	$28.11\ (1 - e^{(-0.0367*DAI)})$	0.75	$34.05\ (1 - e^{(-0.0749*DAI)})$	0.86	NS
Linear model for nitrification					
Manure E	−4.09 + 0.0547*DAI	0.41	−3.61 + 0.1158*DAI	0.71	NS
Manure F	−1.42 + 0.0000*DAI	0.07	9.92 + 0.0691*DAI	0.36	NS
Manure H	8.10 − 0.1434*DAI	0.73	8.38 + 0.0000*DAI	0.17	* (for *b*)
Manure I	8.24 + 0.0000*DAI	0.24	0.96 + 0.0764*DAI	0.44	* (for *b*)

This contrasts with previous work where finer textured soils typically have slower rates and lesser quantities of nitrification (Sørensen et al., 1994) because of physical protection of the substrate. However, the impact of texture, specifically increasing soil clay content, has been inconsistent (Chadwick et al., 2000). In the incubation experiment discussed here, the potential impact of physical protection in the finer textured soil may also have been minimized by the stirring at each sampling date. The remaining manures (E, F, H, and I) grouped together based on a distinctly different pattern of nitrification (Table 3). These manures followed zero-order, linear patterns, although in several cases the slope or rate was not different from zero (manures F and I in sandy loam soil, and manure H in slit loam soil). Manure H resulted in net immobilization (nitrification rate = −0.143 mg N kg^{-1} soil day^{-1}) when incorporated into the sandy soil, but not in the silt loam soil.

Net mineralization of organic N was observed for most manures on both soils (Table 4), as measured by an increase in N_i ($NH_4 + NO_3$), compared to the unamended control soil. The increase in N_i was, in every case, best described by a simple linear regression like that in Eq. 4. For most manures, the mineralization rate varied between 0.08 and 0.12 mg N kg^{-1} soil d^{-1} (Table 4). Some notable exceptions were manure B, with a rate of about 0.16 in both soils, manure D in the silt loam soil, and manure H, which immobilized N in the sandy loam soil. Several manure + soil combinations also resulted in no net mineralization (i.e. slope not different from zero) through the 176 days incubation.

There have been many attempts to establish mineralization rates for manure organic N, so it of interest to see how our results compare with other studies. A typical growing season in a cool environment like Maine, where these soils and manures originated, would accumulate around 2500 degree days (DD) during the growing season, with a base temperature of 0 °C. This means that 100 days of our incubation is similar to a "growing season" (i.e. 100 days × 25 DD d^{-1}). If

Table 4. Net mineralization rates for dairy manures (A through H) applied at rate of 100 mg organic N kg^{-1} soil and inorganic fertilizer N applied at 100 mg inorganic N kg^{-1} soil, during 176 days aerobic incubation in sandy loam and silt loam soils

N source	Net mineralization rate (mg N kg^{-1} soil d^{-1})	
	Sandy loam soil	Silt loam soil
Fertilizer N	0.000[a] bc[b]	0.042[a]bc
A	0.098ab	0.130ab
B	0.160a	0.158a
C	0.115ab	0.061b
D	0.114ab	0.149a
E	0.045[a] b	0.115ab
F	0.004[a] bc	0.091abc
G	0.109ab	0.115ab
H	−0.144d	0.028[a] bc
I	0.031[a]bc	0.048bc

[a]Mineralization rate not significantly different from zero.
[b]Data in the same column with same letter are not significantly different at $P = 0.05$ level.

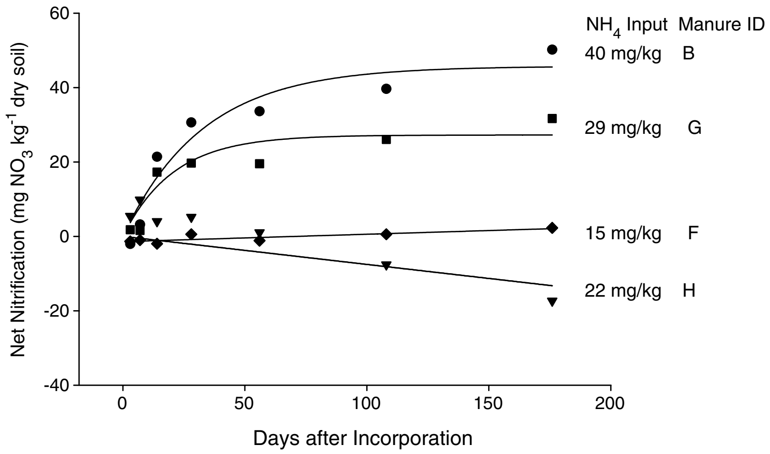

Figure 2. Net nitrification for four dairy manures in a sandy loam soil, corrected for nitrification in unamended soil.

organic N is mineralized at 0.10 mg N kg^{-1} soil day^{-1} (approximately the mean mineralization rate for the manures used here), then 10 mg organic N kg^{-1} soil would be mineralized during that period. Since all manures in this incubation were applied at a rate of 100 mg organic N kg^{-1} soil, this is equivalent to a mineralization rate of 10% per growing season. These mineralization coefficients are similar to those reported by Chadwick et al. (2000), Serna and Pomares (1991) and the average of the manures analyzed by Van Kessel and Reeves (2002). They are somewhat lower than those of Douglas and Magdoff (1991), and the empirically-derived estimates of Klausner et al. (1994). In two previous incubation experiments using similar methods, we noted that apparent mineralization from several manures and slurries was zero, an assumption also made by Paul and Beauchamp (1995). A substantial difference in the current study, relative to our earlier reports, is that the soils here were stirred, sampled, and repacked at each sampling date as was done by Qafoku et al. (2001). This serves to redistribute C and N substrates at each sampling, and presumably would lead to conditions more favorable for microbial transformation, including both mineralization and immobilization.

The substantial differences in net nitrification among manures, even when appreciable NH_4 is present, is illustrated graphically in Figure 2, for manures B, F, G, and H. These manures could be categorized as net nitrifying (B, G), net immobilizing (H), or neither (F), even though all contained NH_4 at the beginning of the incubation (ranging from 15 to 40 mg NH_4–N kg^{-1} soil). This variability stimulated our evaluation of compositional factors, and how they relate to the rate and extent of net N transformation of manure N, based on the initial hypothesis that recalcitrant C in the manure would lead to microbial immobilization of applied NH_4, which is the most readily available N fraction in the manure. Although the recalcitrant C pool could be defined (and quantified) in a number of ways, we used the NDF procedure of Goering and Van Soest (1970), which is widely used to quantify total cell wall concentration of feedstuffs. This, and the similar procedure for acid detergent fiber (ADF; Van Soest and Wine, 1967) have been used for this type of evaluation, most recently by Van Kessel and Reeves (1988). The difference here is in evaluating the relationship between fibrous C and inorganic N, rather than using fibrous C to characterize only the recalcitrance of the organic N pool(s) in the manure. As an example, Figure 3 shows the net rates of NH_4 disappearance and NO_3 evolution (nitrification) for the same manures as in Figure 2 (B, F, G, and H), each incorporated into the sandy loam soil (Figure 3a) and the silt loam soil (Figure 3b). The nitrification of fertilizer NH_4 is also shown for comparison. Although not identical, the net rates of NH_4 consumption at day 7 of the incubation are similar, ranging from 2 to 3.5 and 2.5 to 4 mg kg^{-1} day^{-1}, for the sandy loam and

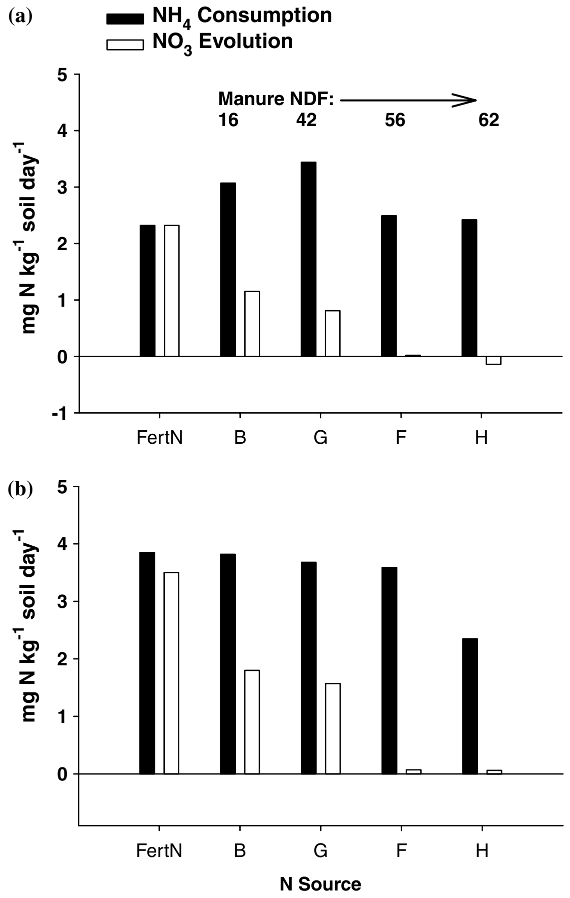

Figure 3. Net NH_4 consumption and NO_3 evolution rates 7 days after incorporating dairy manure into (a) sandy loam and (b) silt loam soils.

silt loam, respectively. At this point in the incubation, all transformations would be expected to be relatively rapid, and the concentration of NH_4 should not limit either immobilization or nitrification rate. In both soils, the nitrification rate for fertilizer N is nearly identical to the NH_4 consumption rate, indicating that all NH_4 is being nitrified. For these manures, however, the rate of nitrification drops quickly as the NDF content of the manure increases (moving from left to right in Figure 3). This is interpreted as net immobilization, which occurs to some extent for all the manure treatments but not for inorganic fertilizer N alone. Manure H is immobilizing the entire supply of NH_4 at this point of the incubation.

Using all nine manures, we evaluated the relationship between individual manure composition factors (total C, total N, organic N, NH_4–N, and NDF), C to N ratios based on either total C or NDF (as a proxy for fibrous C), and five parameters that serve as descriptors of the rate and extent of manure N transformation (nitrification rate at 7 and 56 days after incorporation, net mineralization rate of manure organic N, cumulative N nitrified by day 176, and the proportion of total N nitrified by day 176). This correlative analysis looks only at these pairs of compositional factors and N transformation, and thus is not a complete correlation matrix. The results are shown in Table 5. There are several notable trends evident from these correlations. First, manure N fractions alone (both organic N and NH_4 concentrations) are reasonable predictors of manure PAN, with NH_4 concentration being slightly more so. Second, ratios based on total C (TC) and based on NDF were equally successful; in many cases, the negative correlations with N transformation parameters were identical. Third, the strongest correlations ($r = -0.88$ to -0.90) included ratios of TC or NDF to NH_4 concentration calculated from the $t = 0$ extraction, vs. either total NO_3 accumulation or the proportion of total N that was nitrified during the incubation. These results generally agree with previous reports. Diaz-Fierros et al. (1998), for example, defined manure fiber by particle size (with larger particles being more fibrous), and found that the solid material retained on a 1 mm sieve stimulated immobilization of N when mixed with soil. Likewise, Sørensen (1998) found that as manure C increased (due to increased straw content) N immobilization increased. As mentioned previously, other reports (Chadwick et al., 2000; Van Kessel and Reeves, 2002) demonstrated that fibrous C affects the potential mineralization of manure organic N, but both had intentionally removed the manure NH_4 fraction from the manure. Further evaluation of the interaction between slowly and rapidly degradable C and N in manure is needed to develop better estimates of manure PAN. Typically, PAN is estimated by first assigning the availability of manure NH_4 a coefficient reflecting the management at the time of application, particularly regarding timing of incorporation and plant growth. Then a constant or coefficient is applied for manure organic N availability, following the decay series concept of Klausner et al. (1994). In many cases, this results in a reasonable estimate of seasonal PAN. However, it also masks the potential interactions

Table 5. Linear correlation coefficients (r) between composition of freeze-dried dairy manures and transformation of manure N in soil

Manure factor	r				
	Day 7 nitrification rate	Day 56 nitrification rate	% of organic N mineralized	Day 176 NO_3 concentration	% of total N nitrified in 176 days
Total C (TC)	−0.41[a]	−0.38	−0.47	−0.51	−0.50
Total N (TN)	0.73	0.70	0.66	0.82	0.82
Organic N (Org N)	0.64	0.64	0.61	0.75	0.75
Extr. NH_4	0.79	0.74	0.68	0.86	0.84
Calc. NH_4	0.76	0.73	0.63	0.84	0.83
NDF	−0.68	−0.66	−0.62	−0.80	−0.79
TC:TN	−0.73	−0.76	−0.73	−0.86	−0.87
TC:Org N	−0.67	−0.70	−0.77	−0.82	−0.83
TC:Extr. NH_4	−0.65	−0.71	−0.79	−0.77	−0.78
TC:Calc. NH_4	−0.78	−0.78	−0.79	−0.89	−0.88
NDF:TN	−0.73	−0.76	−0.81	−0.87	−0.88
NDF:Org N	−0.69	−0.72	−0.76	−0.84	−0.85
NDF:Extr. NH_4	−0.66	−0.72	−0.81	−0.79	−0.80
NDF:Calc. NH_4	−0.78	−0.78	−0.80	−0.90	−0.89

[a]All regression coefficients are significant at $P = 0.05$ level.

between manure C and N fractions, and fails to identify specific manures that contain appreciable NH_4 but may still result in net N immobilization after application to soil.

Conclusion

Our research is demonstrates of the interaction between manure C and the microbial transformations of readily-available NH_4. Manure composition affects not only the extent of nitrification of manure NH_4, but also the rate of nitrification during rapid and more stable phases during aerobic incubation in the soil. Using a widely available laboratory procedure (NDF), along with manure NH_4 concentration, it may be possible to develop better predictions of manure PAN.

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